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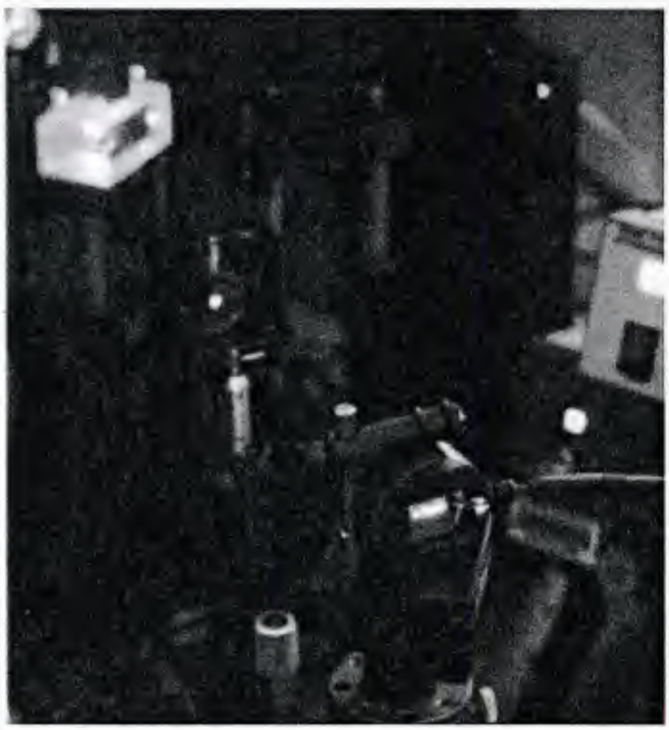
MEMORANDUM

From: Bill Jemison
To: Dr. Daniel Tam, ONR
Date: 12/31/2012

Subject: Progress Report 009–
Chaotic LIDAR for Naval Applications: FY13 Q1 Progress Report (10/1/2012– 12/31/2012)

This document provides a progress report on the project "Chaotic LIDAR for Naval Applications" covering the period of 10/1/2012–12/31/2012.



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FY13 Q1 Progress Report: Chaotic LIDAR for Naval Applications

This document contains a **Progress Summary for FY13 Q1** and a **Short Work Statement for FY13 Q2**.

Progress Summary for FY13 Q1

Significant progress has been made in the demonstration of a wide bandwidth green fiber laser. Previous reports have detailed the generation of wide bandwidth chaotic signals using fiber ring lasers. Amplification of these signals has also been reported, to power levels that allow frequency doubling from infrared (IR, 1064 nm) to green (532 nm). A free space optical system has been previously reported that performed frequency doubling of a continuous wave (CW) 1064 nm source. We now report integration of a wide bandwidth chaotic signal generator, two amplifier stages, and a frequency doubling arrangement. Together, these components comprise a wideband chaotic signal generator at 532 nm which was a significant goal of the project.

We also report progress in simulation of the fiber laser and amplifiers. Previous reports presented steady-state predictions of signal and pump power in the fiber, but we now describe a simulation that gives dynamic signal, pump, and spontaneous emission powers. This simulation gives instantaneous powers at all wavelengths throughout the entire fiber. This allows amplifier simulations not only for CW inputs (as before), but also of highly modulated signals of interest for ranging and imaging (e.g. chaotic wideband). The same simulation methodology will allow simulation of our novel fiber lasers for predictive design aid, and better understanding of how parameters might be optimized to tailor the output signal for specific applications.

High Power Frequency Doubling Circuit

Experimental Setup

The three-stage doubling circuit is shown in Figure 1. The fiber laser source is connected to a preamplifier stage, where the signal power is increased from 70 mW to 120 mW (~3 dB gain) without signal distortion. The output of the preamplifier is fed through a polarization controller to enforce linear polarity. The signal then passes through a main gain stage, where high power pumping boosts the signal above 5 W (>16 dB gain). This high power signal then leaves the fiber and is focused down onto a second-harmonic generating (SHG) crystal. The output beam from this crystal contains high-intensity green light that can be used in underwater LIDAR.

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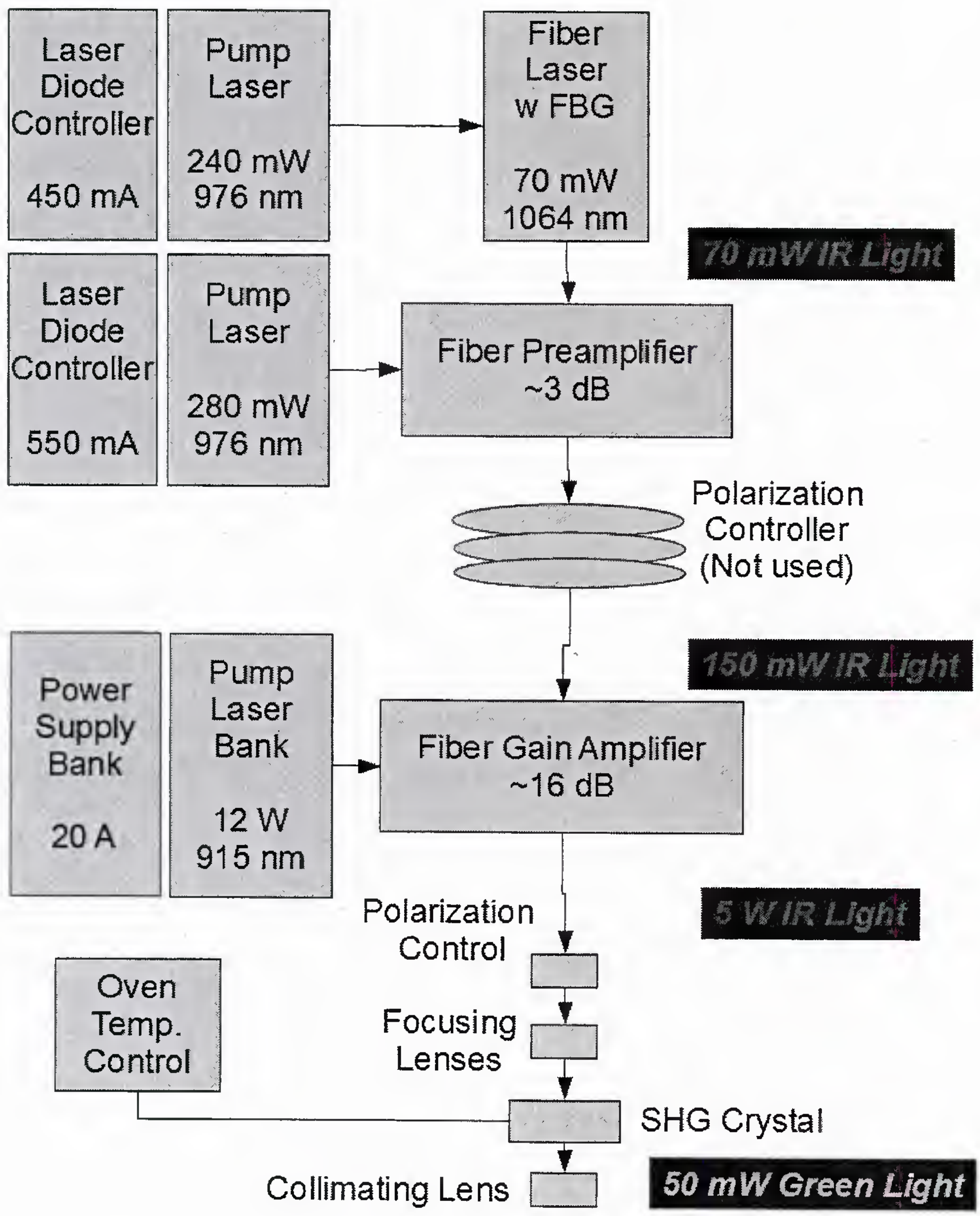

Figure 1. High power frequency doubling circuit. The 1064 nm wide bandwidth fiber laser source passes through a preamplifier, a gain amplifier, and a second-harmonic generating crystal, to produce the desired high-power green signal.

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The fiber laser is a Fabry-Perot (FP) design, whose lasing wavelength is controlled by two 18 GHz (0.1 nm) fiber Braggs gratings. Its output signal is a chaotic wideband waveform where multiple longitudinal modes lase simultaneously. Most of its power is concentrated in the 0-1 GHz spectral segment which is .

In the preamplifier, a single-mode pump and a wave-division multiplexer (WDM) are used to core-pump a short piece of doped fiber. A simple forward-pumped arrangement using ~30 cm of Yb-doped fiber attains 200 mW, before an isolator that reduces the net output to 150 mW while providing protection for the fiber laser. At the output of the preamplifier, the fiber is rotated on a three-paddle polarization controller that forces the polarization to be linear, as is desirable for SHG through the crystal.

The main gain stage is a cladding-pumped amplifier, using high-power, fiber-coupled semiconductor diode lasers to pump a multimode fiber. A pump-signal combiner handles mode matching between the passive pumped fiber, the signal fiber and the active double-clad Yb-doped fiber. The signal level at the end of the double-clad fiber is well above 5 W. The residual pump light is forced out of the fiber, and the usable signal is then collimated to free space for frequency doubling in the crystal. Back reflections are mitigated by bandpass filters at the pump diodes, and an angle-cleaved fiber tip at the output.

A series of free-space lenses collimate and focus the infrared beam as it exits the fiber. The beam is focused on the center of the SHG PPKTP crystal. This crystal has a quadratic efficiency curve, so that the green output goes as the square of the IR input. After separating the green from the residual IR, the usable green output is seen to be about 50 mW, which is collimated for use in the water.

The benchtop setup is show in Figure 2.

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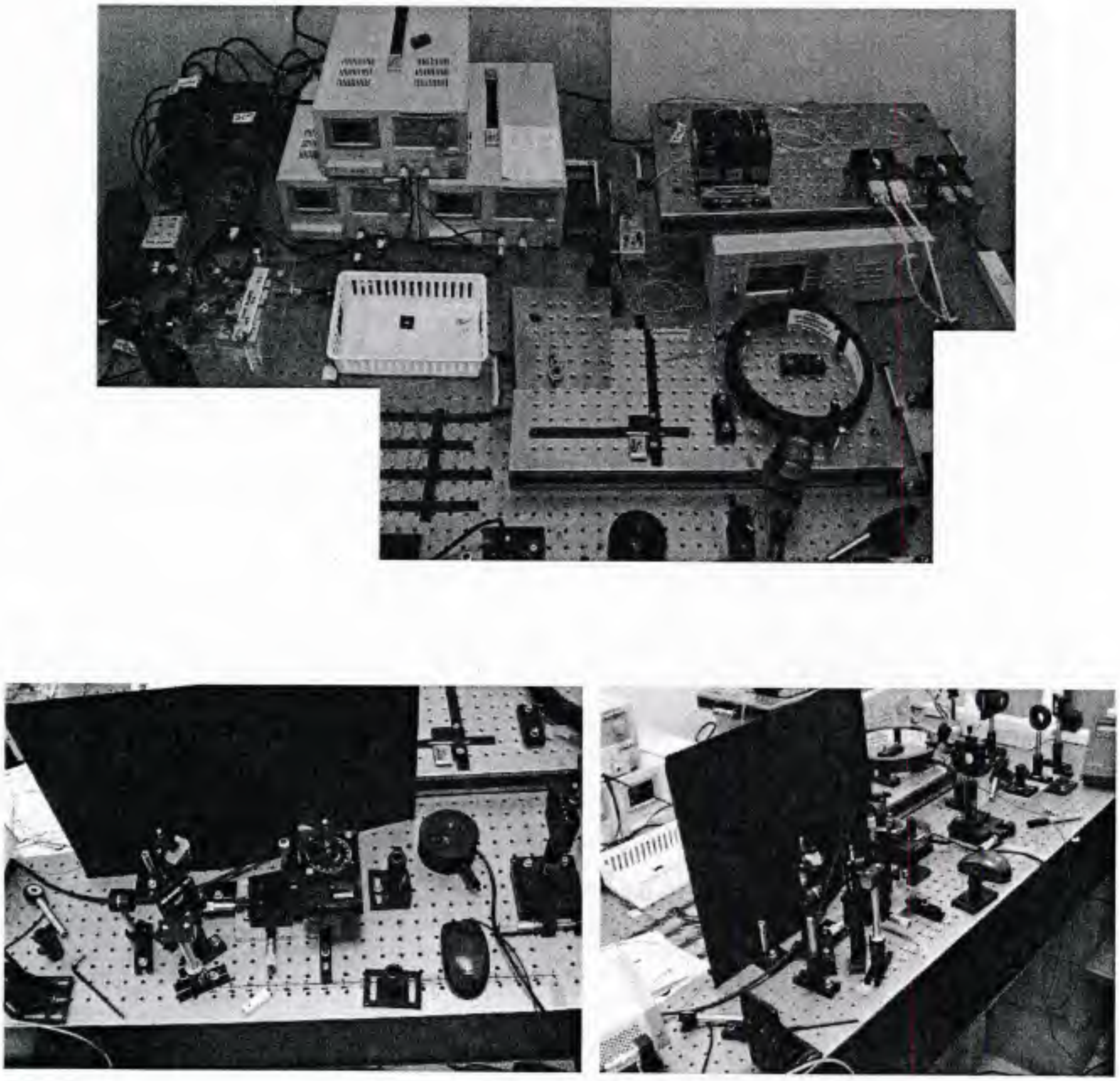

Figure 2. Lab setup at Clarkson University. A high power green output is produced by integrating the fiber laser, fiber amplifiers, and free space frequency doubling optics.

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Experimental Results

The output signal power for the laser, amplifiers, and frequency doubler are shown in Figure 3. The preamplifier's ~3 dB gain is modest but it nonetheless compensates for component losses throughout the fiber system. It also ensures that the gain amplifier sees enough signal power to prevent amplified spontaneous emission (ASE).The gain amplifier shows a 16 dB net gain for the signal. Further improvements could increase this gain significantly, since experiments suggest that some signal power is lost at the fiber output. Improving the amplifier efficiency is a subject of ongoing investigation.

The green power out of the frequency doubler follows the quadratic efficiency curve specified by the crystal supplier (with the exception of a 52 mW data point that we feel is an outlier, possibly caused by beam shaping issues). The power output falls close to the expected levels, although polarization control of the IR light will improve the doubling performance. (The crystal only acts on a certain light polarity, so the IR beam will ideally be completely linearly polarized; there is currently no polarization control and so the beam is highly elliptic.).

The RF modulation pattern at the output of the crystal is the same as that at the input, as shown in Figure 4. There is no visible frequency-domain shaping imposed by the crystal, so we are confident that this doubling process is an effective way of converting infrared signals of interest to green signals that can be used for underwater ranging and imaging. While efficiency improvements are possible in all stages of the system, this result is a significant step that shows the feasibility of this approach to generating high power underwater sources.

It should also be noted that the fiber laser currently used is a short-cavity version that was assembled specifically to drive the amplifiers and doubler, so it needs modification to generate the quasi-continuous wideband chaotic signal previously reported. Specifically, a long passive fiber must be added to reduce its mode spacing from the current 19 MHz to the desired ~1 MHz. This will allow execution of the desired experiments.

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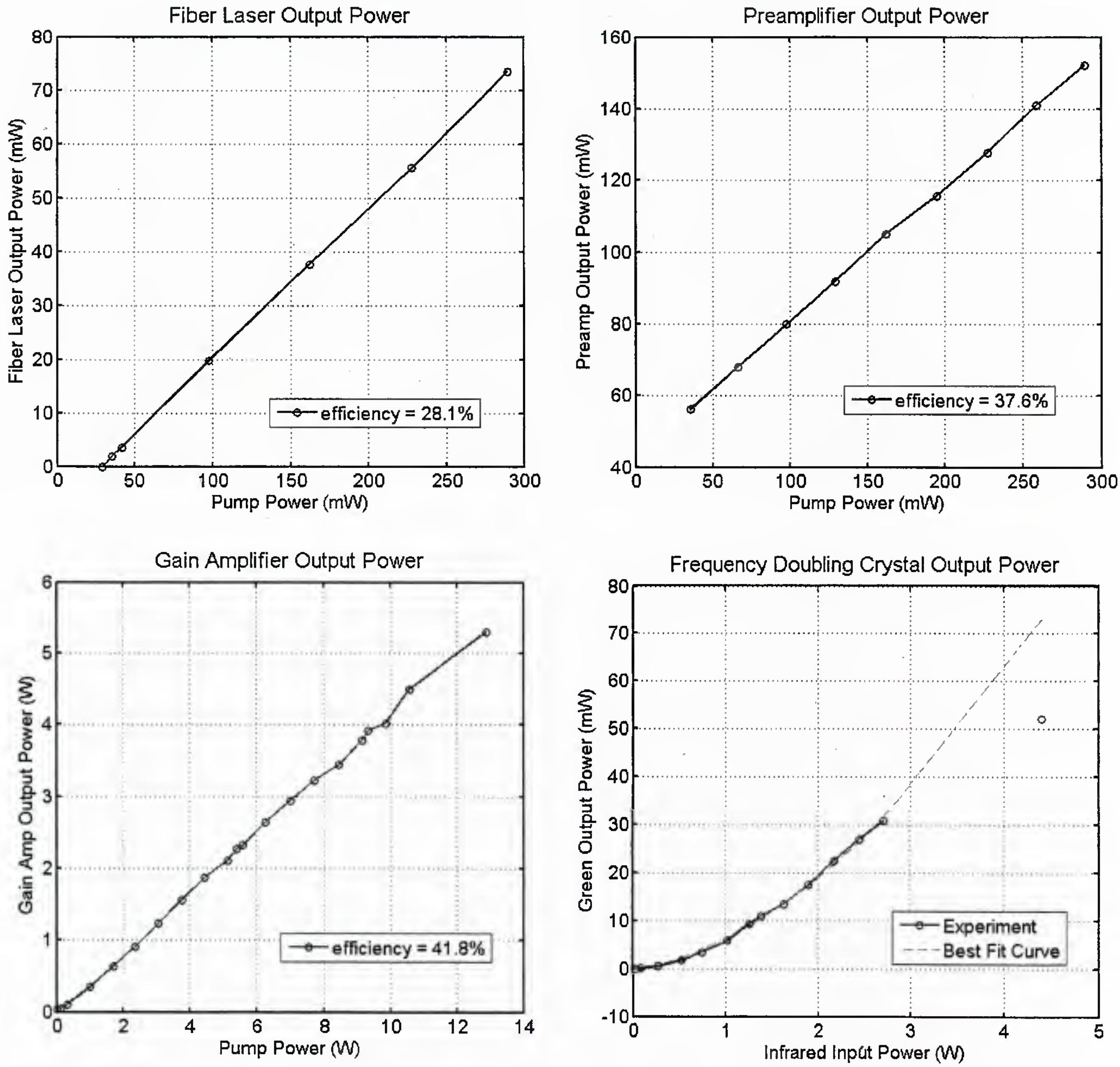

Figure 3. Output power curves for green laser system. *Previous Page*: Photograph of the laser. *Top left*: The fiber laser produces 70 mW at 1064 nm at 28% efficiency. *Top right*: The preamplifier boosts this 70 mW input to 150 mW at 37% efficiency, compensating for system losses. *Bottom left*: The gain amplifier boosts 150 mW to 5 W at 42% efficiency. *Bottom right*: The crystal generates over 50 mW green light from infrared, at an efficiency proportional to the square of the infrared power.

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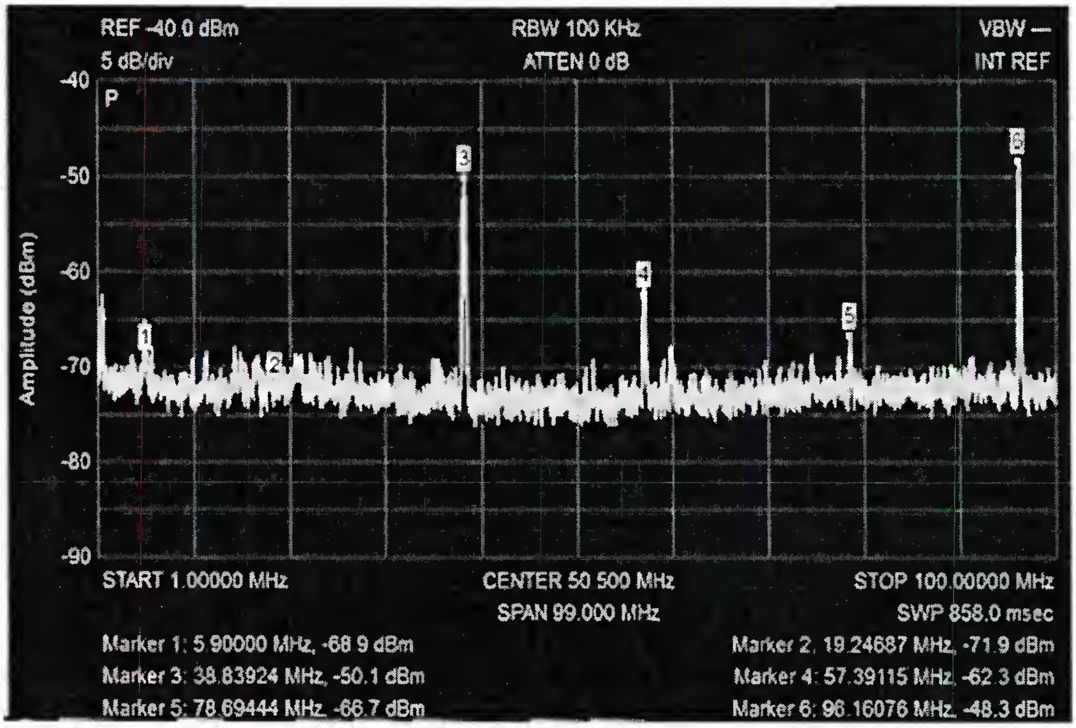
RF Modulation out of Gain Amplifier



RF Modulation out of Frequency Doubler

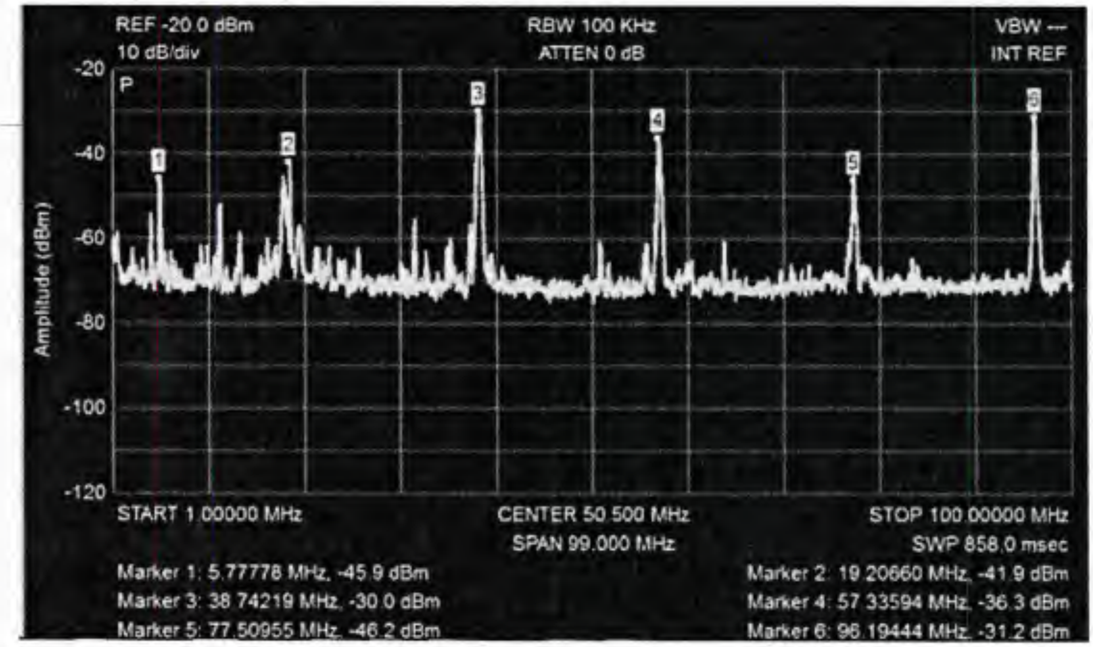


Figure 4. Output signal for gain amplifier and frequency doubler crystal. *Top*: The RF modulation on the signal going into the crystal. *Bottom*: The RF modulation on the signal leaving the crystal. The frequency doubling process does not seem to affect the modulation signal.

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Planned Experiments

Having integrated the stages and assembled a high power wideband chaotic green source, we turn now to the system experiments designed to prove the usefulness of this source for underwater lidar work (these are collectively labeled as Task 3 in the original project proposal). Design and setup of these experiments will be done in conjunction with further improving the chaotic green source itself.

The quasi-continuous wideband spectrum of this source suggests use as a frequency probe, useful as a transmissometer for characterizing frequency response of various water types to intensity-modulated light. A near-term experiment that we propose to run is to test the frequency response of forward and backward scattering. We intend to do this by passing this chaotic green source through clean and then progressively more turbid water, as in Figure 5. As the turbidity increases, we hypothesize that the effects of backscatter will increase at the low frequencies (0-100 MHz), and the effects of forward scatter will be seen at the high frequencies (500-1000 MHz). Since the source has strong, continuous frequency content across this 0-1 GHz spectrum of interest, the "transfer function" of the turbid water can be deduced by comparing the power spectral density at the output of the turbid water with the power spectral density of the signal at the output of clean water. This will reveal which transmission frequencies can be efficiently used at various turbidities. Similar experiments could be run against other water variables as desired.

The wideband green signal has a strong, sharp correlation peak, which makes it ideal for unambiguous, high resolution ranging. Correlation-based approaches to wideband "noise radar" or "chaotic signal radar" has been proven by several lidar and radar research teams, and can be used with our signal as well, as shown in Figure 6. Proximity detection is straightforward using a fixed delay line, with electrical analog components after an optical-to-electrical conversion using a photodetector. Actual range detection can also be done by digitizing the signal, and the signal correlation peak is so sharp that ranging would be sampling-rate limited (i.e. the time-resolution of the ranging would correspond to the Nyquist frequency of the sampling used). Recent simulations have indicated that analog subtraction may be an alternative to digitization that also makes good use of the wide bandwidth for unambiguous and high resolution range measurements. System experiments using either correlation or subtraction will be performed in the near future to prove the concept of wideband ranging using this source.

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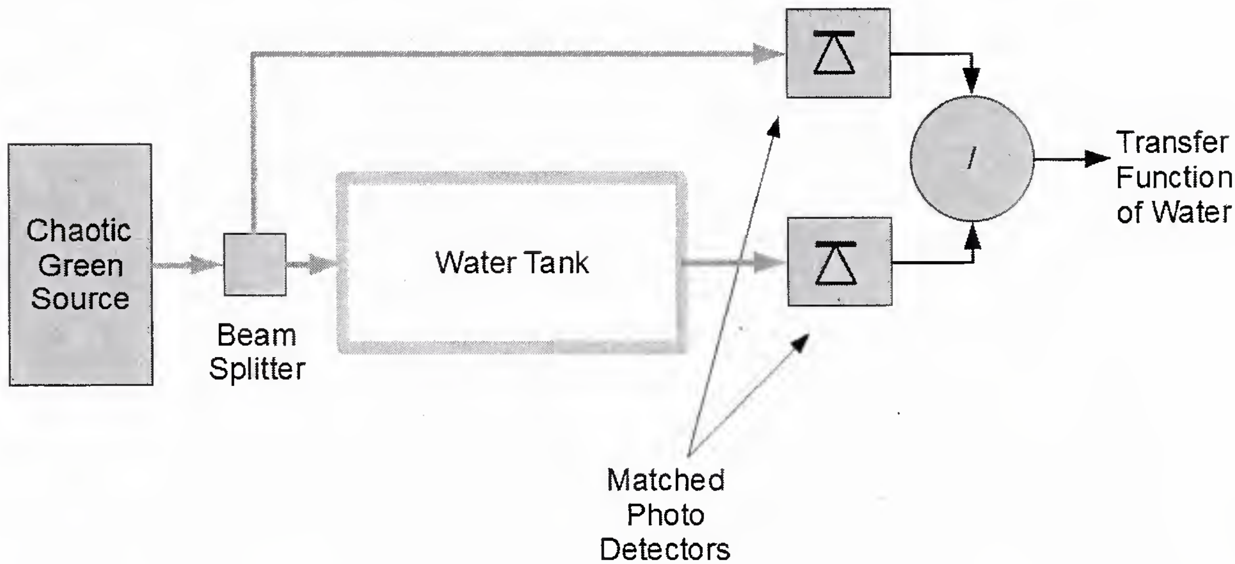

Figure 5. Planned transmission experiment. The chaotic green source transmits its multimode signal through the water and through the air simultaneously. By dividing the signal received through the water tank by the signal through the air, the transfer function of the water can be deduced, and preferred operating frequencies identified.

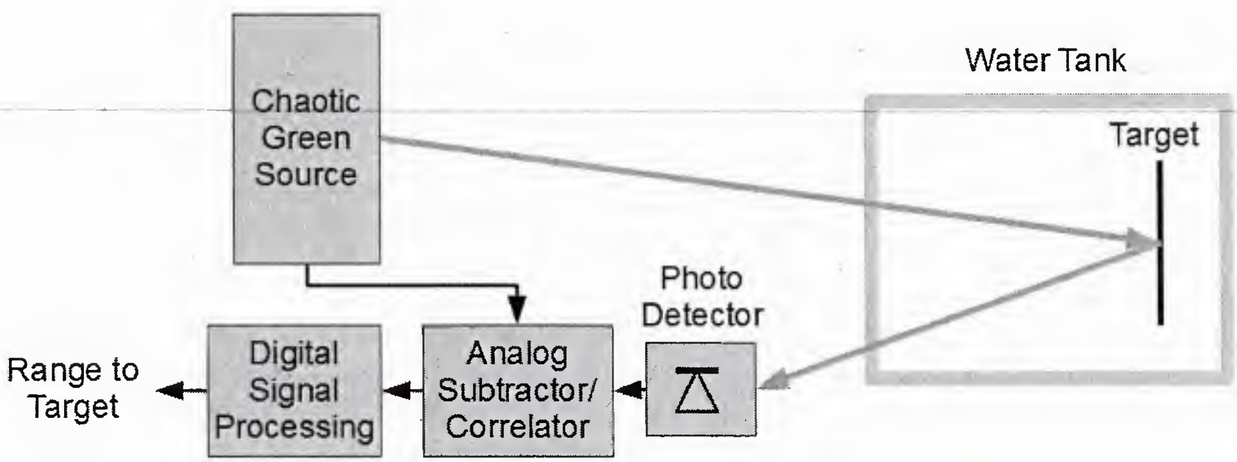

Figure 6. Planned ranging/proximity detection experiment. The chaotic green source transmits its multimode signal through the water to a target, where it reflects back to a receiver and is processed. By performing subtraction or correlation of the transmitted and received signals, the range to the target can be calculated.

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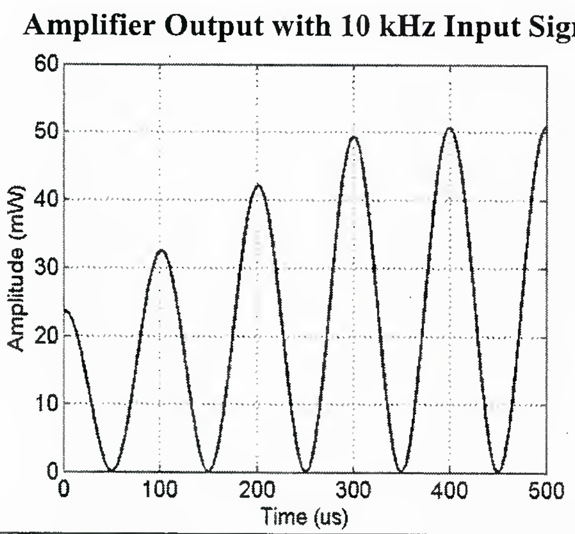
Dynamic Modeling of Fiber Amplifiers and Lasers

Accurate modeling of the fiber amplifiers and lasers will allow predictive design and will suggest improvements for more accurate ranging and imaging. Previous simulations of the fiber amplifiers have relied on ordinary differential equation (ODE) solutions, which are able to solve for the signal and pump powers throughout the fiber at a steady-state. They are not, however, able to calculate the powers as a function of time, so the transients and dynamics of the system are lost. We have recently implemented a partial differential equation (PDE) solution of the amplifiers, which calculates the powers both as a function of location in the fiber and of time. The advantage of this approach is that the modulation on the input signal is accounted for, and the response of the amplifier to the modulated signal is clearly seen.

Figure 7 shows a sample simulation result: the pump and signal powers at the fiber ends are plotted as function of time. Here, the modulation on the signal is a simple sinusoid, and the output reflects this input modulation, albeit with a transient amplitude envelope as the power in the fiber builds up. This and similar simulations give insight into the sorts of waveforms that can be used for ranging and imaging; limits on frequency, symbol rates, amplitude changes, and pulse widths can all be explored.

Fiber lasers can also be simulated using these PDEs. Our wideband chaotic fiber lasers get their novel behavior from the interaction of multiple longitudinal modes, which can be explored using an enhanced version of this simulator. Accurate simulation of the fiber lasers may allow predictive tailoring of their unique waveforms for higher range resolution, more efficient power transfer, etc.



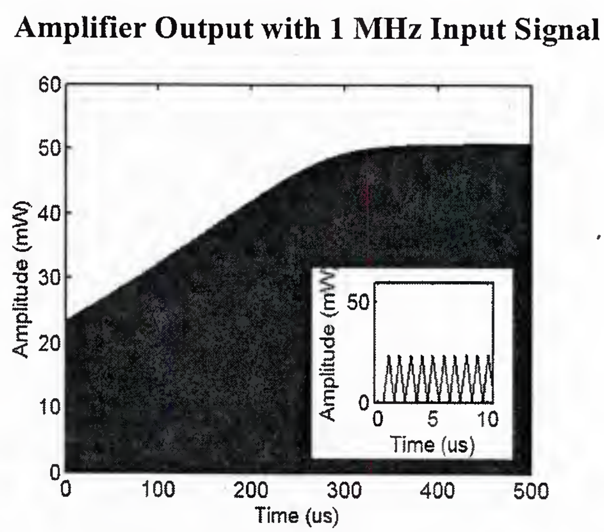


Figure 7. Dynamic simulation of fiber amplifier response to modulated input signals. *Left*: The transient build-up of the amplitude can be seen. *Right*: The fast oscillation of the input signal is replicated at the output, giving confidence this modulation frequency can be accurately amplified.

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Summary

A high power wideband chaotic green source has been assembled and tested. Previous chaotic signal generation, amplification, and frequency doubling techniques have been integrated to create this source for underwater work. Clear next steps towards efficiency improvements are noted.

Simulations that accurately solve fiber amplifier dynamics have been performed, allowing the development of simulations for the unique chaotic fiber lasers used in this project.

Short Work Statement for FY13 Q2.

The source presented here will be improved by increased efficiency of amplification and doubling, and by modification of the chaotic source signal to be flat, wideband, and quasi-continuous across the 0-1 GHz spectrum of interest.

Once the laser has been characterized, we will begin system demonstration testing to determine the underwater channel characteristics.

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